

“Wound Field and Hybrid Synchronous Machines for EV Traction with Brushless Capacitive Rotor Field Excitation”

2020 DOE Annual Merit Review

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Illinois Institute of Technology**

Project ID: elt230

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Overview

Timeline

- Start Date: 10/1/17
- End Date: 9/30/20 (No-Cost Extension)
- Percent Complete: 85%

Budget

- Total project funding
 - DOE's Share: \$999,752
 - Partner's Cost Share: \$112,955
- FY 17 DOE Funding: \$438,561
- FY 18 DOE Funding: \$383,679
- FY 19+ DOE Funding: \$177,512

Barriers

- Cost of EV traction motors resistant to decrease
- Rare earth permanent magnet (PM) market subject to significant price and supply volatility
- Power factors of IPMSM and IM increase power electronics cost

Project Partners

- Illinois Institute of Technology
 - Lead
- University of Wisconsin-Madison
- Lucid Motors (Atieva)

Relevance/Objectives

Overall

- Develop cost effective wound field synchronous machines (WFSMs) and hybrid excitation synchronous machines (HESMs) which meet DOE cost and performance metrics
 - Final FY20 prototype targets: peak power ≥ 55 kW, continuous power ≥ 30 kW, specific power density ≥ 1.6 kW/kg, volumetric power density ≥ 5.7 kW/l, Cost ≥ 4.7 \$/kW
 - Will also be compared with USDRIIVE 2025 targets
- Develop cost effective and robust capacitive power coupler (CPC) for brushless rotor field excitation power transfer
- Create advanced torque/current regulation algorithms for WFSMs and HESMs
- Evaluate the performance and cost of final prototype WFSM using the capacitive power coupler

This Period

- Final prototype WFSM achieves peak power ≥ 55 kW, specific power density ≥ 1.6 kW/kg, volumetric power density ≥ 5.7 kW/l with CPC
- Final cost evaluation show WFSM with CPC is $\leq \$4.7/\text{kW}$

Milestones

Milestones & G/No-Go Decision Points	Date	Status
Initial journal bearing capacitive power coupler (CPC) prototype 1 meets initial power transfer metrics in s	3/31/17	Complete
Construction of best in class full power WFSM or HESM rotor prototype 1 complete	9/5/17	Complete
Best in class full power WFSM or HESM prototype 1 meets reduced peak power metrics using brushes during dynamometer testing	12/25/17	Complete
Journal bearing CPC prototype 1 transfers $P_{avg} \geq 300$ W and $P_{peak} \geq 600$ W during bench testing	9/29/17	Complete
Rated field current through journal bearing CPC prototype	12/30/18	Complete
PCB CPC design meets initial power transfer metrics	3/30/18	Complete
Final prototype WFSM/HESM design meets power density metrics in simulation	10/17/18	Complete
Construction of final WFSM/HESM prototype complete	Planned 6/30/20	On-going
PCB CPC prototype transfers $P_{avg} \geq 300$ W and $P_{peak} \geq 600$ W during bench testing	7/24/18	Complete
Final WFSM/HESM prototype meets USDRIVE 2020 metrics with brushes and slip rings	Planned 7/30/2020	On-going
Final WFSM/HESM prototype meets USDRIVE 2020 metrics with CPC	Planned 8/31/2020	On-going
Final WFSM/PMWFSM with integrated brushless power coupler BOM achieves $\leq \$4.7/\text{kW}$ target	Planned 9/30/2020	On-going

Approach

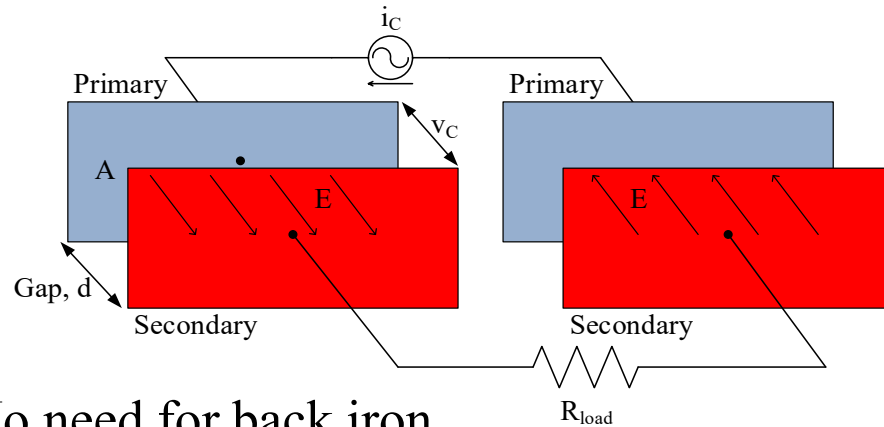
WFSM Power Density and Cost Reduction Approaches

- Die compressed windings (targeting ~70% to 80% slot fill)
 - Flexible number of turns compared to bar/hairpin winding
 - Reduced AC losses at high frequency compared to hair-pin winding
 - Single thermal mass with no air voids
 - Potential to use aluminum wires with similar performance to 40 to 45% fill copper windings with significant cost and weight savings
 - Fractional slot concentrated winding maybe required for stator
- Reduced scrap designs
 - Leverage segmented, cut-core and roll-up techniques on stator and rotors
 - Potential to utilize lower grade electrical steel in rotor
- Fully utilize machine's active materials
 - Refine in-house developed optimization tool and explore the use of topological optimization
- High performance controls development for WFSMs

Approach

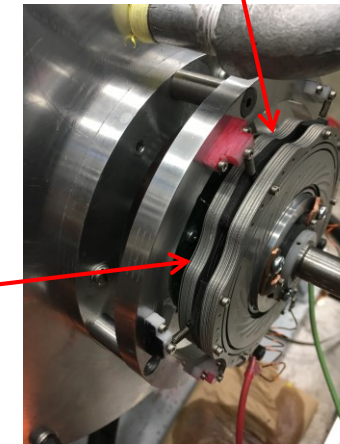
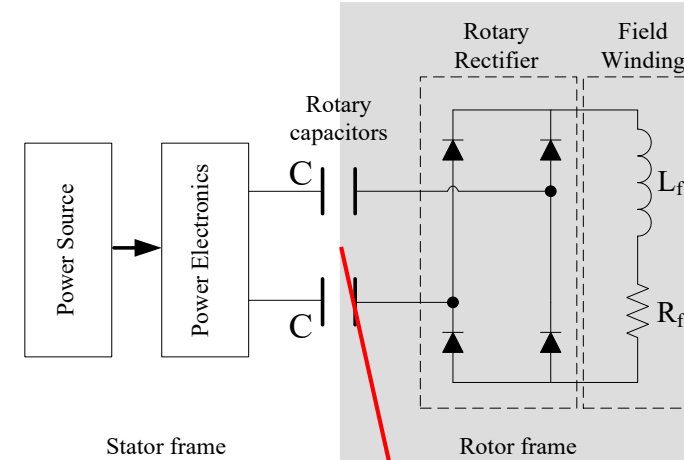
- Capacitive power transfer (CPT) to rotor field winding
 - Power transfer to WFSM field winding through electric field between rotary capacitors

Basic Concept



- No need for back iron
- Electric flux lines terminate on charge, limited field outside of gap
- Previous project used stacked anodized aluminum disks with spiral groove to form axial flux hydrodynamic coupling capacitors

CPT for WFSM Concept



Approach

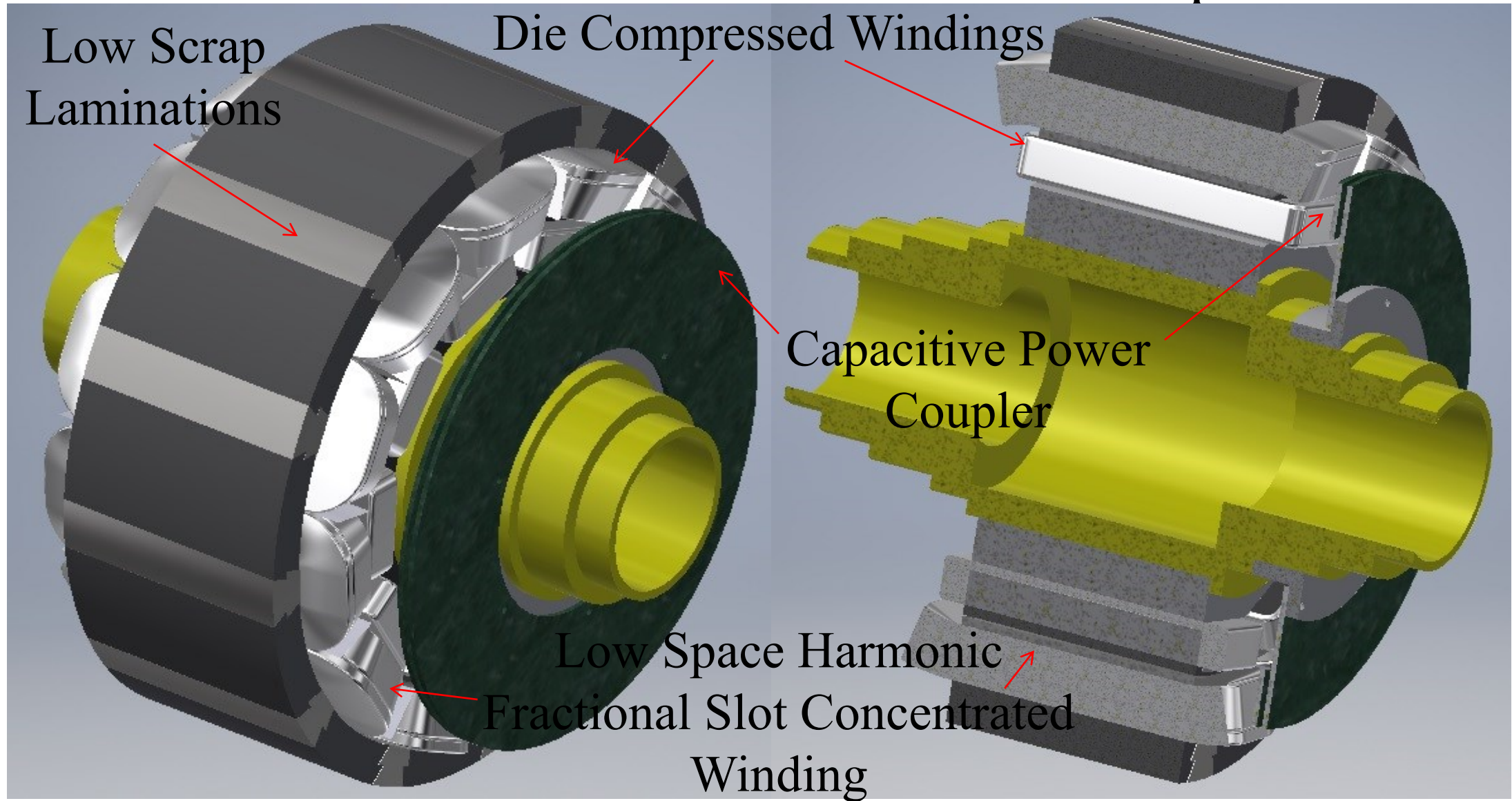
Lower the cost of the capacitive power coupler

- Increase the frequency (MHz) to shrink required capacitance (A/Hz)
- Lower losses in the converter by operating in soft switching
 - Reduced thermal management and reduced switch rating
- Via OEM feedback use simple PCB for low cost and established production technology
 - Reduced capacitance

Develop Hybrid Excitation Synchronous Machines (HESMs) to lower field power requirements

- Bias the flux for most common operating point in drive cycle
- Reduce the amount of PM material compared to full PM machines
- Extend constant power speed range compared to full PM machines

Overall Machine and CPC Concept



WFSMs and HESMs Prototype Development Plan

- Incremental development approach
 - Each prototype will target a specific cost reduction approach/technology
 - Every prototype is targeted to meet USDRIVE 2020 power conversion targets

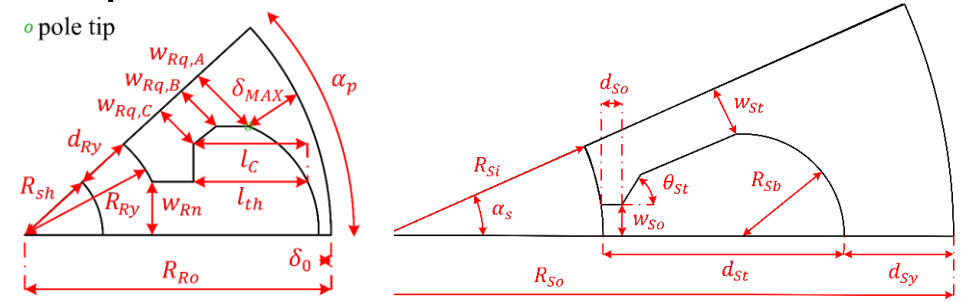
 - Prototype 1: Increased power density classical WFSM (Finished)
 - Prototype 2: Parallel flux dual rotor HESM (Finished)
 - Prototype 3: WFSM rotor with die compressed field winding (Finished)
 - Prototype 4: 3 phase wound rotor HESM (Waiting on motor shell availability)
 - Prototype 5: Final WFSM/HESM stator and rotor with die compressed windings (Under construction)
-
- Integrate prototype 5 with CPC

Previous Technical Accomplishments

- Baseline WFSM with random wound rotor and distributed winding stator prototyped
- Rotor with rectangular die compressed field windings prototyped
- Hybrid excitation synchronous machine with parallel rotors prototyped
- High and low switching frequency deadbeat direct torque and flux control of WFSMs
- Decoupling matrix current regulator
- Several capacitive power coupler (CPC) technologies investigated
 - Journal bearing CPC
 - Integrated LC PCB
 - Large gap PCB CPC; Three and single phase versions
- Minimization of parasitic capacitances and dielectric loss in CPC PCBs
- Large gap 3 phase CPC with MHz, soft switching, 3 phase GaN inverter prototyped and tested

Technical Accomplishments – Multi-Material Magneto-Structural Topology Optimization

- Traditional WFSM finite element analysis (FEA)/magnetic equivalent circuit (MEC) design methods
 - Utilize geometric template => dimensional parameters
 - Dimensional parameters are generally not truly independent
 - Geometric template time consuming to create and make robust
 - Magnetic and structural analysis are often done separately with a structural check of the final design
- Topology optimization
 - Optimally distribute material in a free-form manner in a design domain
 - No need of pre-defined geometric template
 - More design degrees of freedom to create small features => mesh size
- Design-based topology optimization methods
 - Normalized material density ρ as control variable, such that $0 < \varepsilon \leq \rho \leq 1$
 - Force densities to ε or 1 by material property penalization

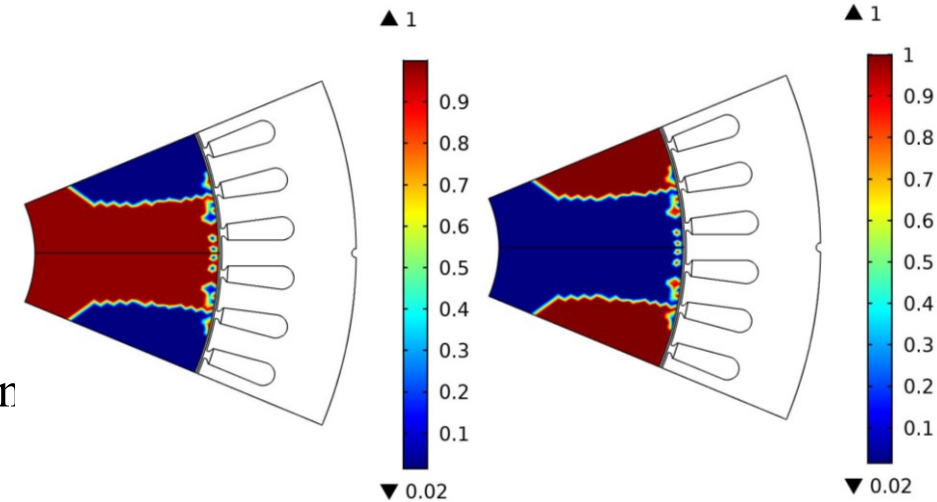
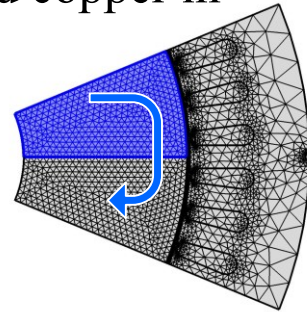


Technical Accomplishments – Multi-Material Magneto-Structural Topology Optimization

- Multi-material topology optimization of WFSM rotor
 - Three materials (Electric steel, copper, air)
 - Normalized material densities ρ_{Fe}, ρ_{Cu} in each rotor mesh element correspond to electrical steel and copper in WFSM
 - Additional control variable for rotor current density, J
 - Each element can only be one of the materials ρ_{Fe}, ρ_{Cu} ; constraint of $\rho_{Fe,k} + \rho_{Cu,k} \leq 1$

$\rho_{Fe,k}$	$\rho_{Cu,k}$	Material
1	0	Electrical steel
0	1	Copper
0	0	Air

- Multi-material magnetic only topology optimization
 - Un-manufacturable design
 - Need to account for structural forces and support copper field windin



Electrical steel distribution

Copper distribution

Technical Accomplishments – Multi-Material Magneto-Structural Topology Optimization

- Copper and electrical steel self-weighting body forces are structural loads, f

$$\begin{array}{c} \text{Element displacement} \searrow \\ \text{Stiffness matrix} \longrightarrow \end{array} K_S u = f \longleftarrow \text{Structural load} \quad f = \frac{m_{Fe,Cu,k} v_{Fe,Cu,k}^2}{r_{Fe,Cu,k}}$$

- Stress and constraint
 - P-norm aggregation to form a single stress constraint that approximates the maximum stress in the design domain

$$s_{PN} = \left(\sum_{n=0}^k \frac{1}{a} s^P \right)^{1/P} \leq k_{sf} s_{yield}$$

- Compliance constraint to ensure rotor deformation less than small fraction of airgap
 - Total compliance is found by integrating the strain energy W_s within the design domain Ω

$$C = \int W_s d\Omega \leq C_0$$

- Globally Convergent Method of Moving Asymptotes (GCMMA) and mass thresholding function to avoid intermediate materials

$$M = \begin{cases} M_{Fe,Cu,k}, & \rho \geq \rho_c \\ 0, & \rho < \rho_c \end{cases} \quad \rho_c = 0.5 \text{ in this work}$$

Technical Accomplishments – Multi-Material Magneto-Structural Topology Optimization

• Optimization Results

Three Different Objective Functions and Constraints

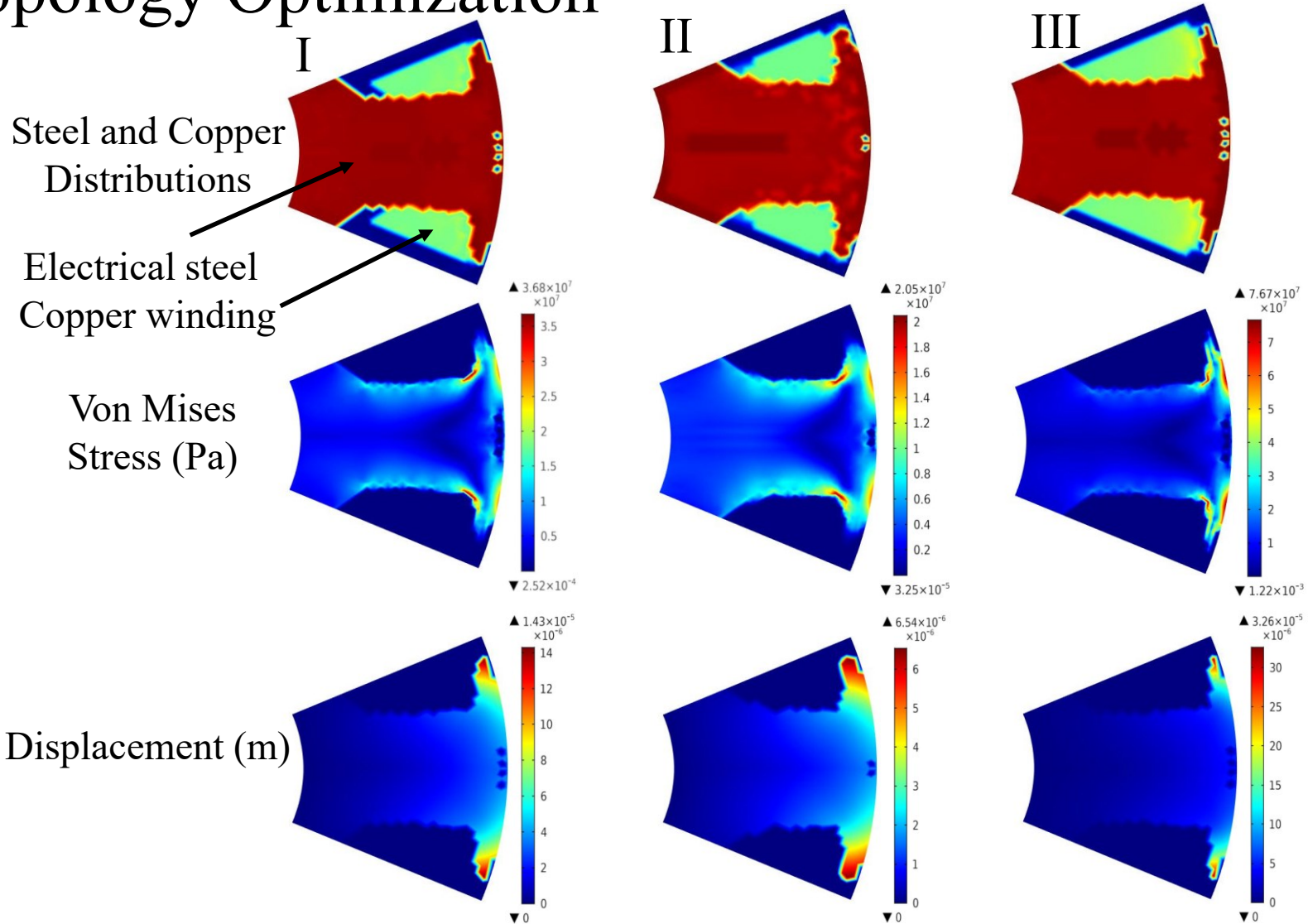
	Example 1	Example 2	Example 3
Speed (RPM)	4,000	4,000	4,000
T_{avg} (Nm)	256	240	376
T_{ripple}	10%	9.9%	9.1%
L_{Cu} (W)	486.76	470.41	666.41
Active rotor copper volume (mm^3)	24000	22600	31900
Total Ampere-turns (A-turns)	2160	2031	2871
s_{max} (MPa)	36.8	20.5	76.7
Total Rotor Mass (kg)	7.12	7.54	7.68
u_{max} (mm)	0.014	0.0065	0.033
Compliance (J)	0.19	0.15	0.5

Steel and Copper Distributions

Electrical steel
Copper winding

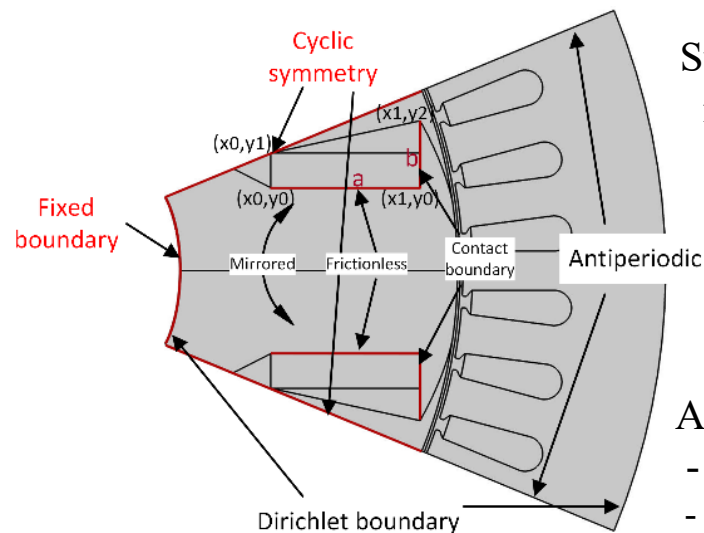
Von Mises Stress (Pa)

Displacement (m)



Technical Accomplishments – Multi-Material Magneto-Structural Topology Optimization

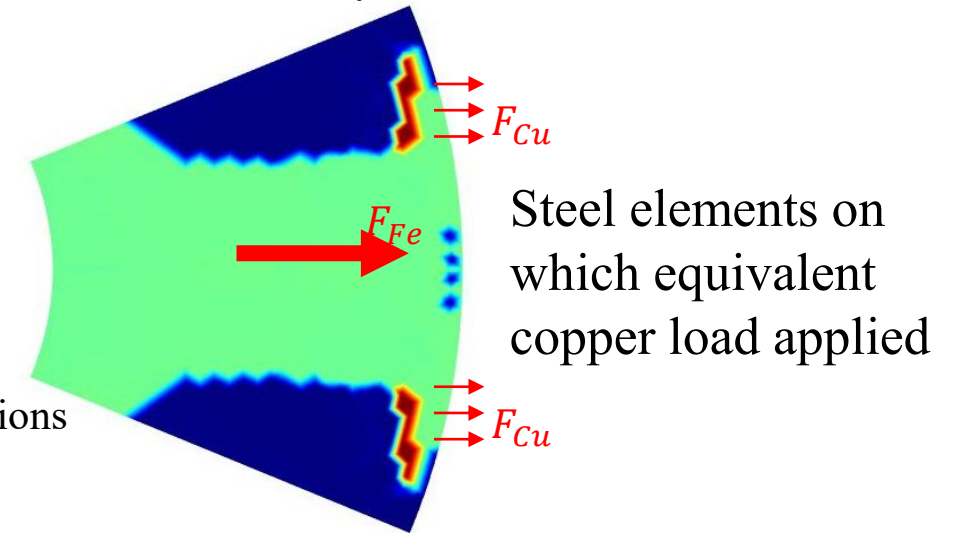
- Virtual Copper Region
 - Create a virtual copper region to approximate frictionless and contact boundary conditions
 - By default, copper is implicitly assumed bonded to the electric steel; more realistic case is that the copper is not bonded with the electrical steel
 - Turn off copper mechanical properties and keep conductivity property
 - Results in unbonding the copper from the electrical steel
 - Calculate the equivalent body load of the copper winding and only apply it as a force on the electrical steel elements at the interface between the copper/iron in the area of the contact boundary



Structural boundary conditions (red) and magnetic boundary conditions (black)

Approximate WFSM mechanical boundary conditions

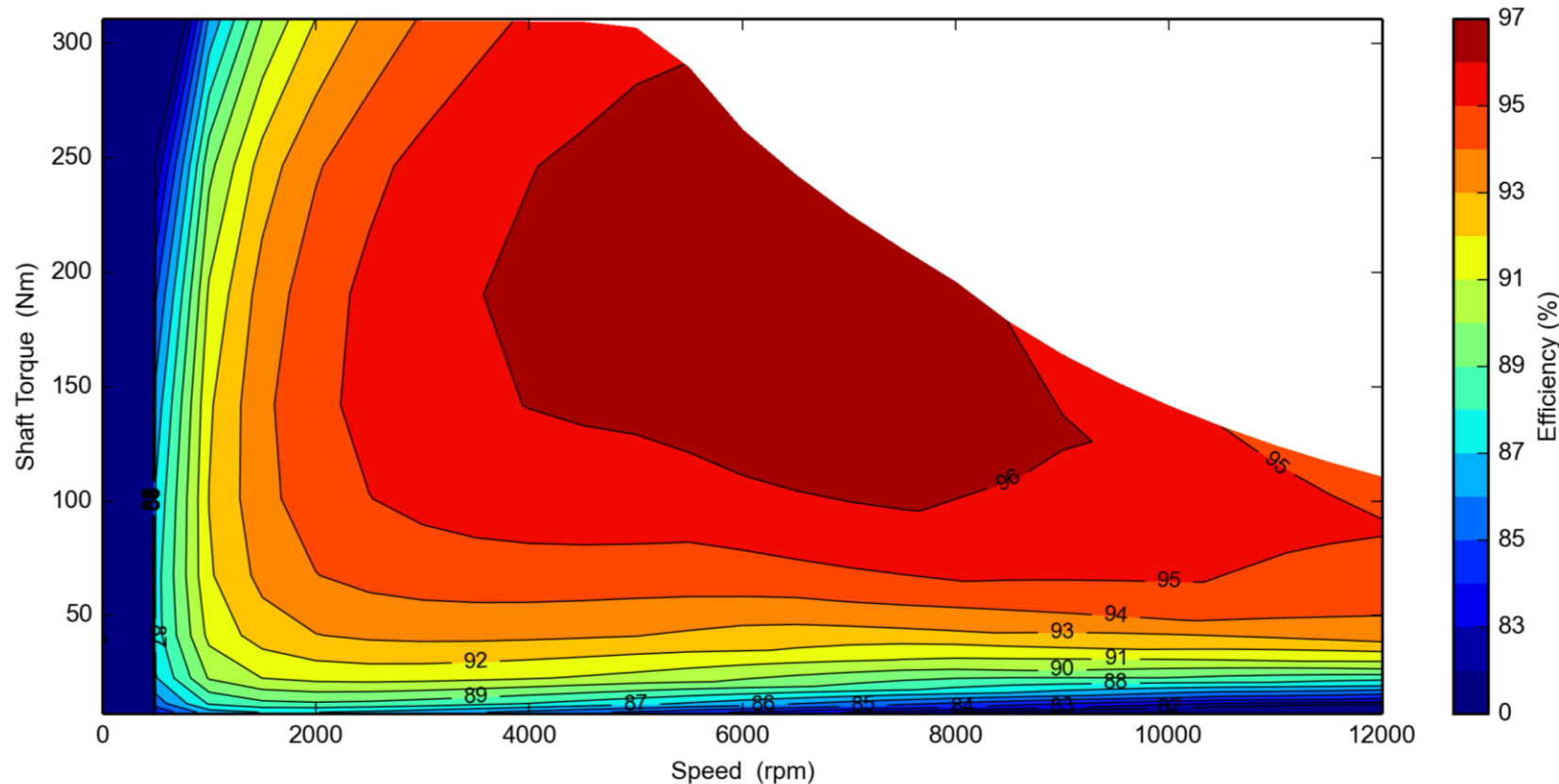
- Frictionless boundary, **a** (reality not really frictionless)
- Contact boundary, **b**



Steel elements on which equivalent copper load applied

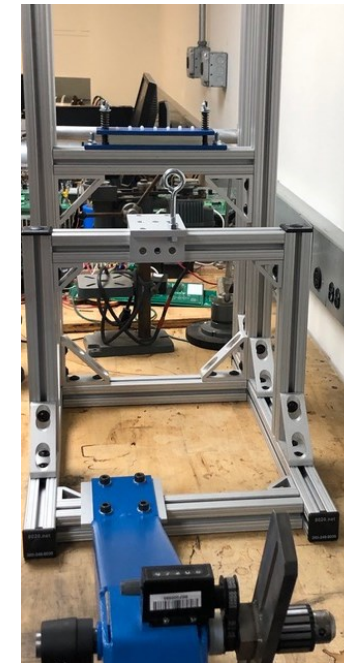
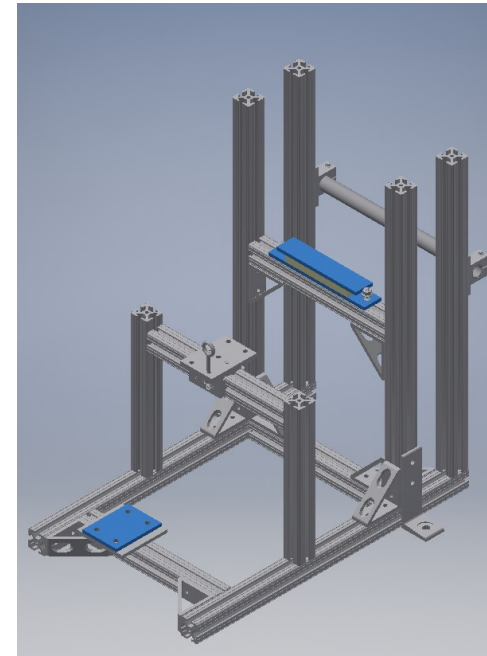
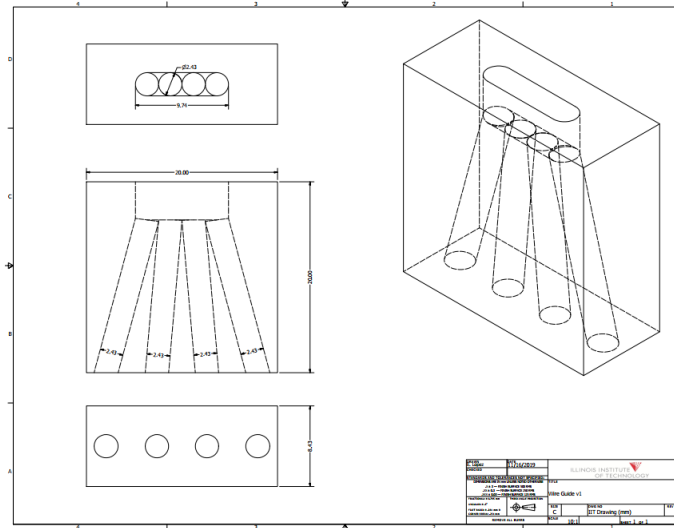
Technical Accomplishments – Mapping of Final Prototype Predicted Performance

- Final WFSM design with die compressed stator and rotor windings efficiency map
 - Winding temperatures of 40 Deg. C assumed
- Large region of high efficiency

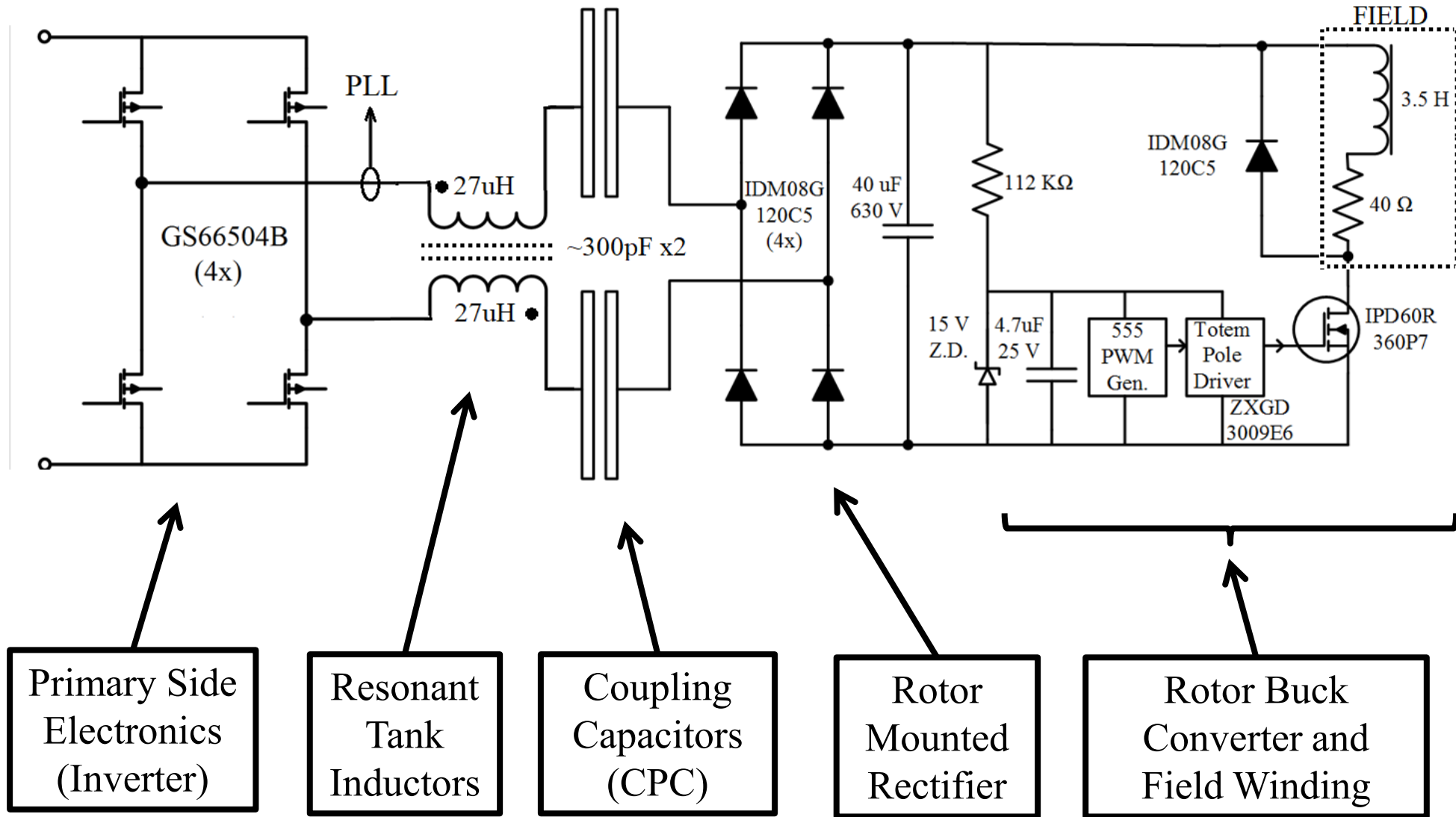


Technical Accomplishments – Winding Setup for Multiple Strands in Hand on Stator Bobbin

- Stator winding requires multiple strands in hand to use reasonable wire gauge during compression process
- Thick, small gauge wire (e.g. AWG 11) work hardens quickly making orthocyclic layout on the bobbin before compression difficult
- Multiple strands in hand laid in an approximately linear orthocyclic manner on bobbin before compression
 - Capability to tension up to 6 strands simultaneously

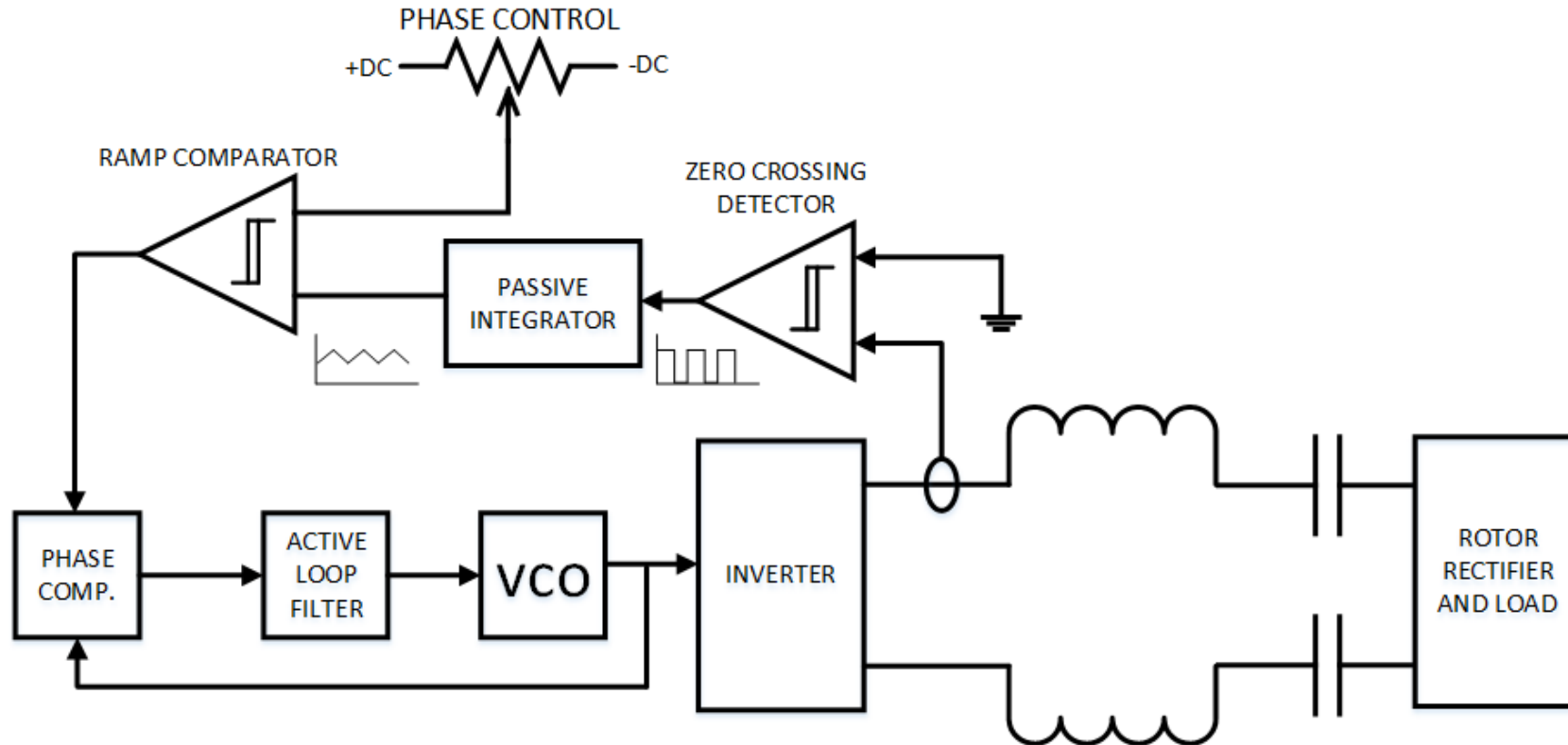


Technical Accomplishments – Final CPT System Schematic



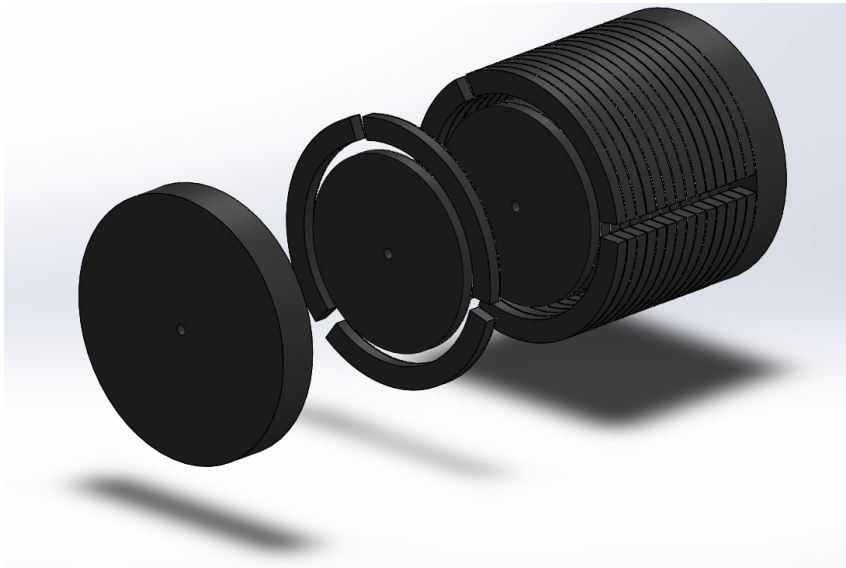
Technical Accomplishments – Automatic Frequency Tracking

- A Phase Locked Loop (PLL) adjusts frequency to maintain soft-switching resonant operation
- Constantly maximize inverter efficiency without user intervention

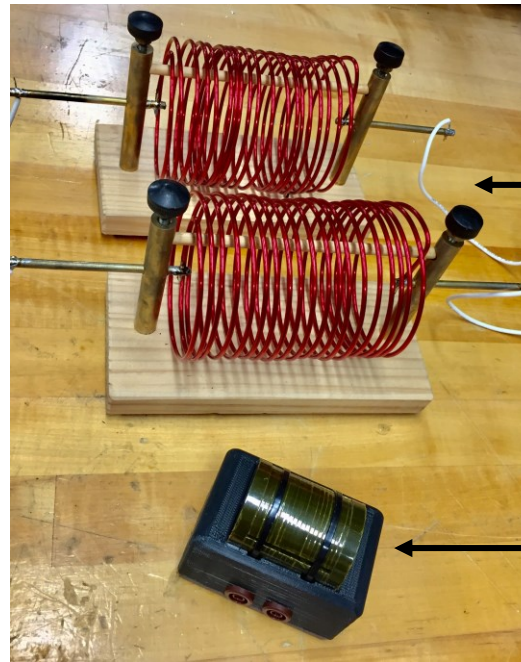


Technical Accomplishments – Low Loss High Frequency Inductors

- Many high frequency capacitive or inductive power transfer systems utilize air core inductors
 - Air core inductors have a very poor volumetric inductance
- New Ferrite high frequency inductor designed, prototyped, and tested
 - Design based on an MIT distributed airgap concept
 - Resonant tank has high voltage and requires high voltage standoff capability



Custom Ferrite sections

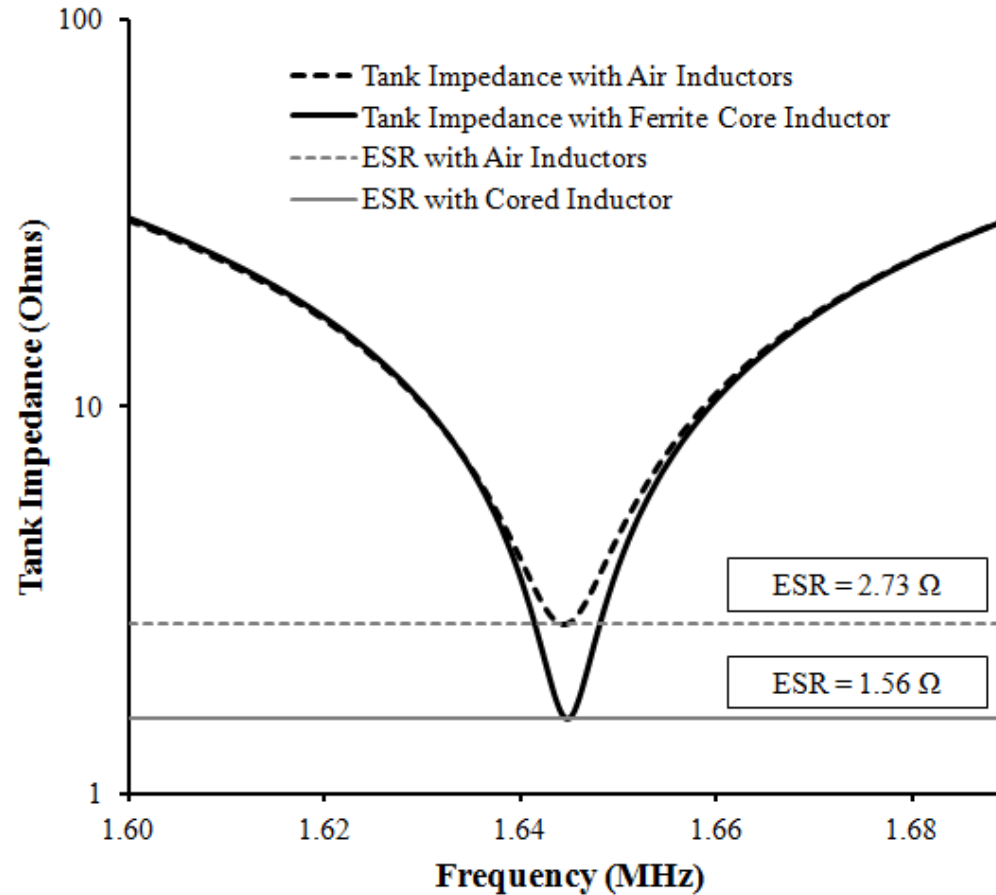


Air core inductors

High voltage Ferrite distributed airgap resonant tank inductor

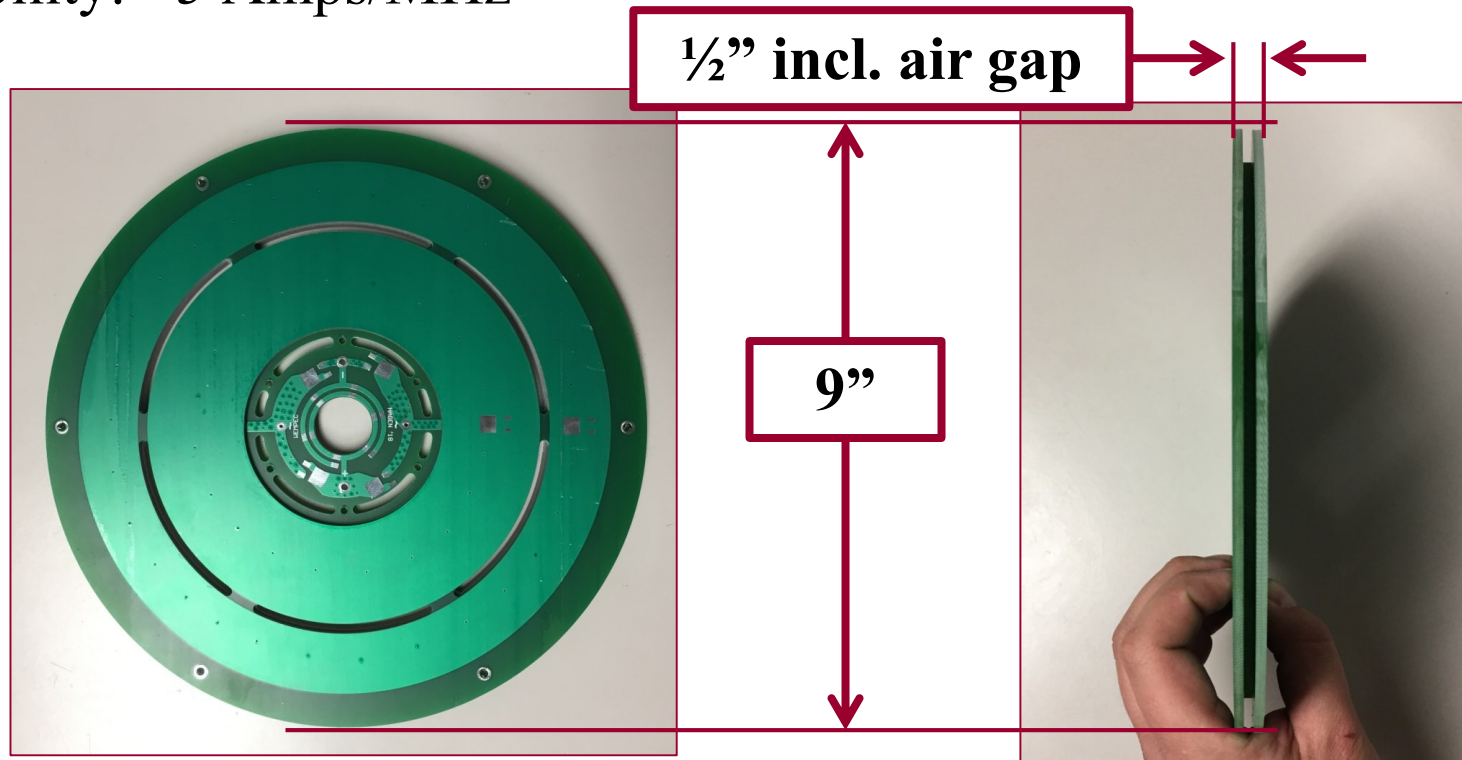
Technical Accomplishments – Low Loss High Frequency Inductors

- Comparison of resonant tank air core and newly designed ferrite core inductors
- Substantially reduced equivalent series resistance => increased system efficiency



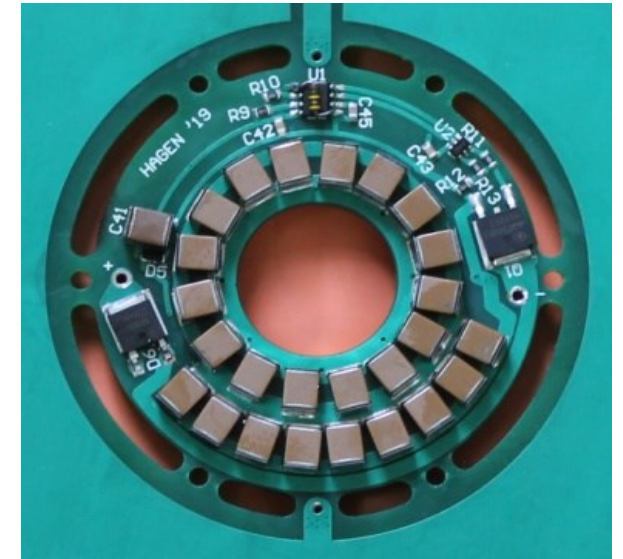
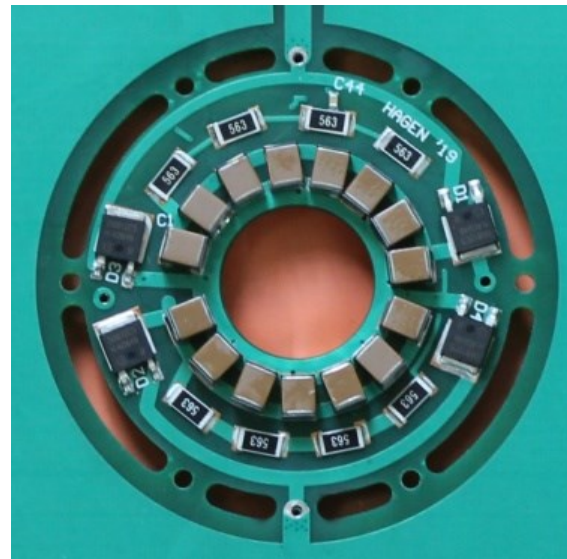
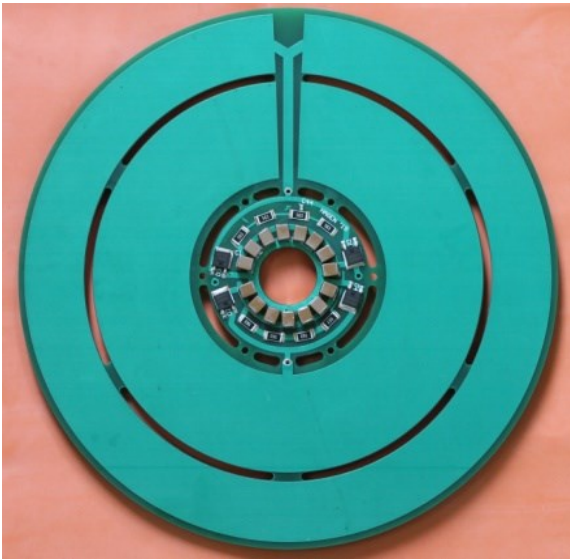
Technical Accomplishments – Final Single Phase Capacitive Power Coupler

- Capacitance per section: ~ 300 pF
- Maximum voltage capability, $V_{C,max} > 3\text{kV}$ (not operating near this limit)
- Current capability: ~ 5 Amps/MHz



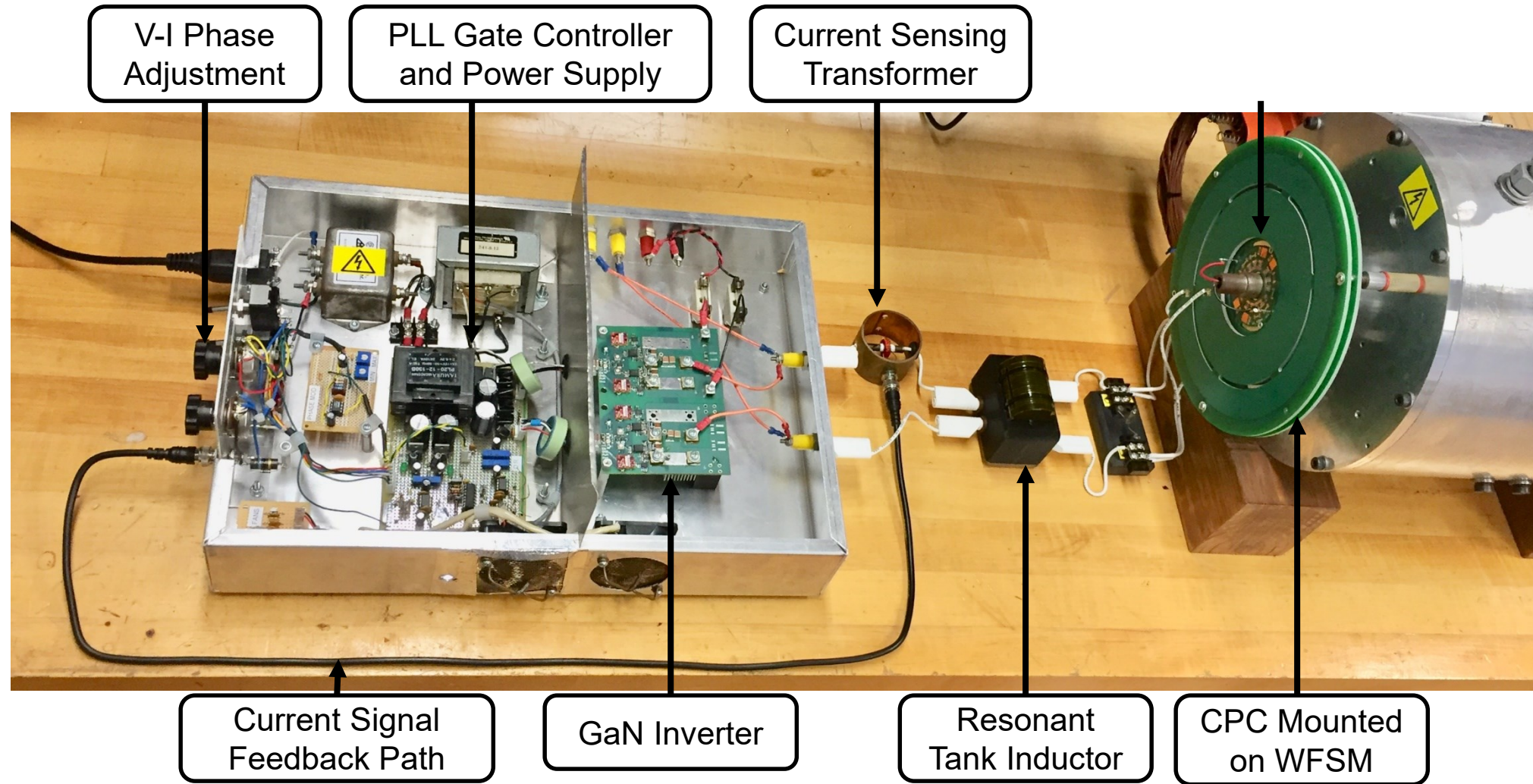
Technical Accomplishments – Final Single Phase Capacitive Power Coupler Prototype with Rotor Mounted Buck Converter

- Impedance transformation using rotor mounted buck converter
 - More flexibility in field winding design while increasing effective impedance of load as seen by the CPC
- Rotor mounted buck converter specifications
 - $f_{\text{switching}} = 1770 \text{ Hz} \Rightarrow$ low switching frequency \Rightarrow high efficiency
 - Duty ratio = 67 %
 - Buck gate drive powered by high voltage DC bus for fully self-contained operation on WFSM rotor



Technical Accomplishments – Final Capacitive Power Transfer System

Experimental Setup



Technical Accomplishments – Final Capacitive Power Transfer System

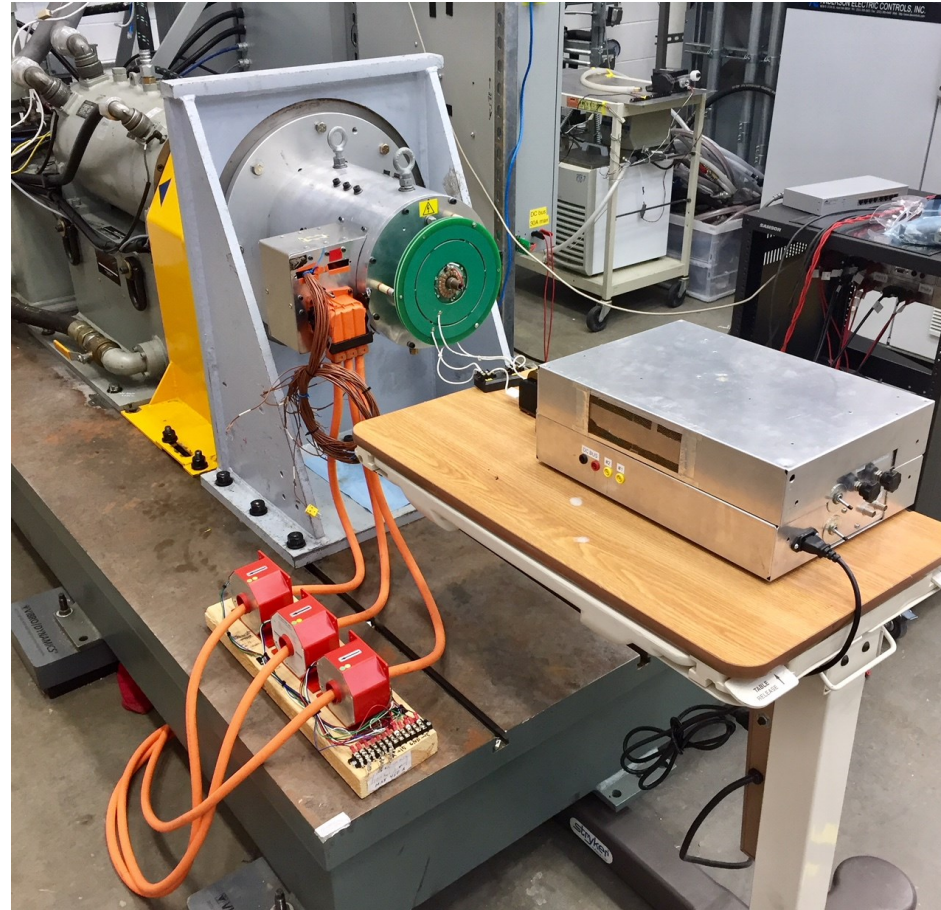
Experimental Results

- Operating Frequency: 1.680 MHz

V_{in}	I_{in}	V_{out}	I_{out}	P_{in}	P_{out}	Eff	I_{ac}	V_{Lrms}
(volts)	(amps)	(volts)	(amps)	(watts)	(watts)	(%)	(amps)	(volts)
108.27	1.03	65.27	1.53	111.52	99.86	89.55	1.614	465
152.06	1.47	88.84	2.26	223.53	200.78	89.82	2.346	676
189.59	1.76	110.01	2.74	333.68	301.43	90.33	3.090	890
219.41	2.02	126.98	3.15	443.21	399.99	90.25	2.869	826
247.80	2.24	142.55	3.51	555.07	500.35	90.14	3.436	989
269.54	2.48	159.57	3.77	668.46	601.58	89.99	3.680	1060
282.42	2.65	168.89	4.00	748.41	675.56	90.27	3.974	1144

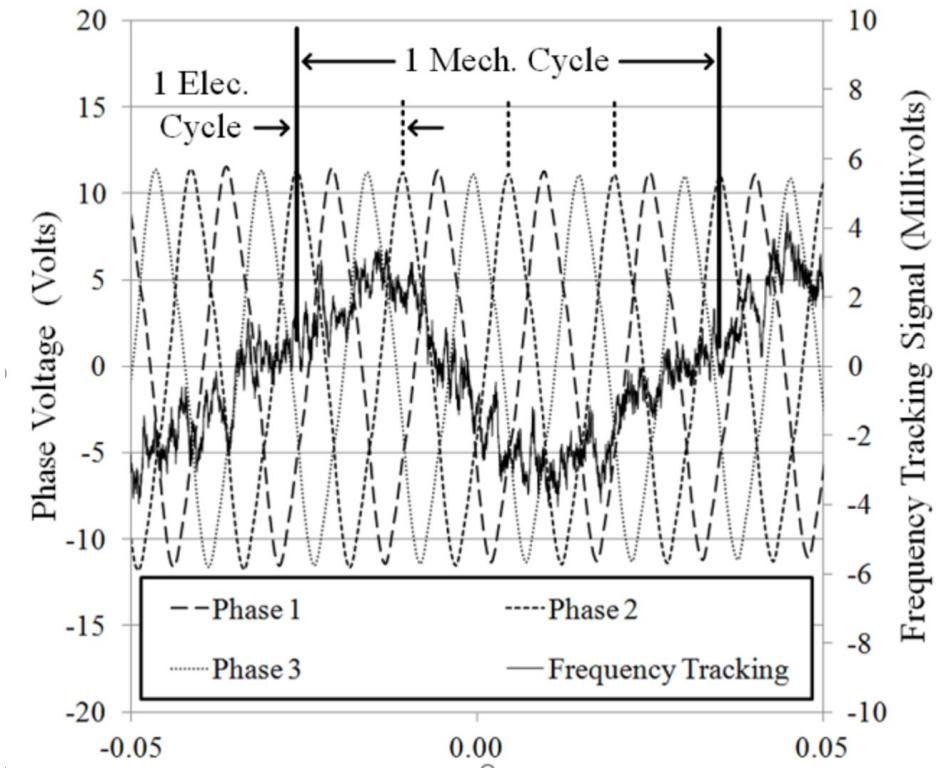
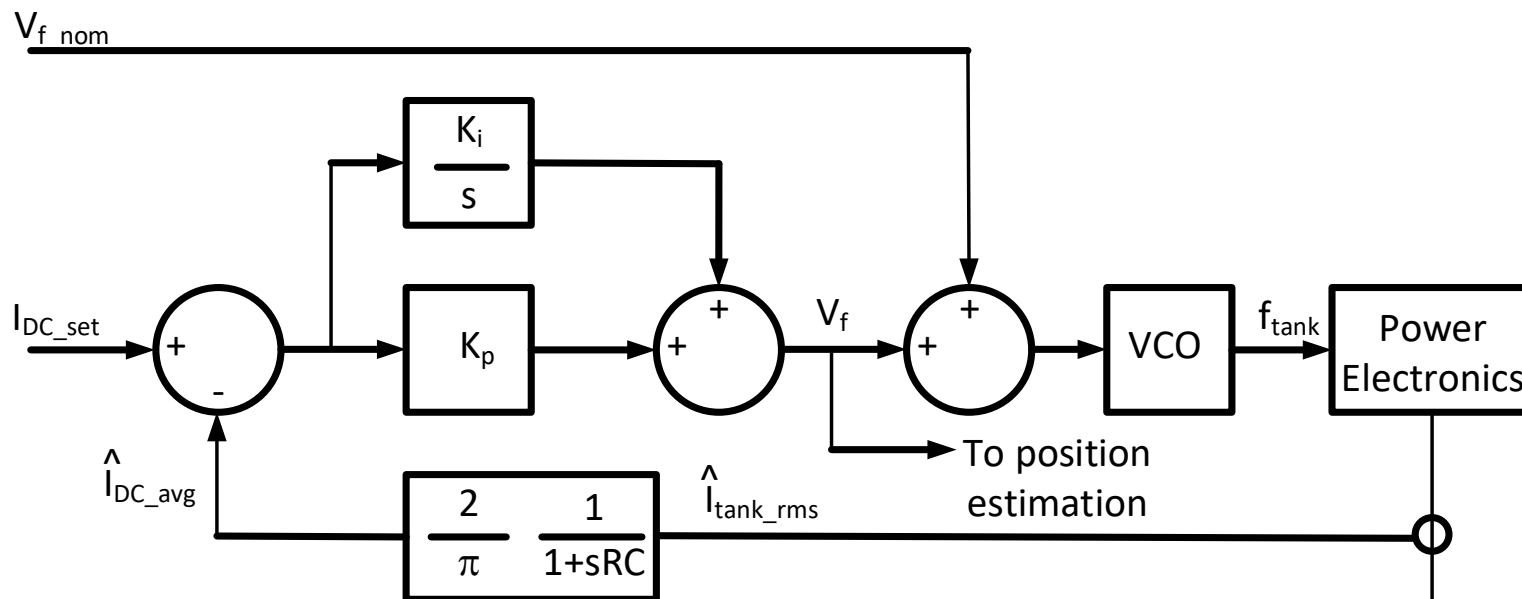
Technical Accomplishments – Final Capacitive Power Transfer System Tested on Dynamometer

- Final CPT tested with earlier WFSM prototype
 - Will be tested with final WFSM prototype when UW-Madison dynamometer reopens



Technical Accomplishments – Extension of Frequency Tracking to Position Self-Sensing via Capacitive Power Coupler

- Potential to replace resolver for position estimation and field orientation
- Circuit must self-tune; Frequency tracking using PLL and VCO
- Additional saliency can potentially be designed into the PCB



Response to Previous Year Reviewer's Comments

- Reviewer Comment: The reviewer remarked that the team has been able to design an excellent power coupler with high efficiency. The hybrid excitation looks very promising at this point. The reviewer said it will be very good if the team can compare the final prototype against U.S. DRIVE 2025 targets. The reviewer noted that collaboration and coordination between the groups seem to be excellent, and proposed future research will address the remaining technical barriers.
- Response: We plan on comparing the final prototype performance and estimated cost versus U.S. DRIVE 2025 targets
- Reviewer Comment: The reviewer remarked some aspects are relevant, but a fair comparison to a baseline IPM is needed. Also, testing the prototype will help confirm the analysis results as well as show any unforeseen issues.
- Response: We will compare the achieved performance of the final WFSM prototype versus information available for state-of-the-art IPM designs. We agree that testing of the prototype will help confirm predicted performance and if there are any unforeseen issues especially in manufacturing of the prototype.

Collaboration and Coordination with Other Institutions

- Illinois Institute of Technology (1 PI, 2 PhD Students)
 - Electromagnetic, thermal, and structural design of WFSM and HESM
 - Development of control strategies for WFSM and HESM
 - Responsible for prototyping and testing of WFSM and HESM
- University of Wisconsin-Madison (1 PI, 1 PhD Student)
 - Design and construction of capacitive power coupler
 - High power dynamometer testing
- Lucid Motors
 - Design reviews of WFSM, HESM, and CPC
 - Assistance with cost estimation

Remaining Challenges and Barriers

- IIT and UW-Madison campuses are currently closed by state mandated “shelter at home” orders
- This impacts the project in several critical areas
 - Parts of WFSM final prototype housing (IIT Machine Shop)
 - Winding machine (IIT Prof. Brown’s Lab)
 - Large presses for die compression (IIT Civil Engineering Department)
 - Assembly of segmented laminations (IIT Machine Shop and Prof. Brown’s Lab)
 - High power dynamometer final testing (UW-Madison WEI Building)

Proposed Future Research

- Finish construction of final WFSM prototype with die compressed stator and rotor windings
- High power dynamometer test final WFSM prototype with brushes and slip rings
- High power dynamometer test final WFSM prototype with PCB CPC
- Evaluate final WFSM prototype versus USDRIVE 2020 and 2025 targets
- Detailed cost evaluation of final design and PCB CPC

Any proposed future work is subject to change based on funding levels

Summary

- Relevance
 - WFSMs and HESMs offer a low system cost path for widespread adoption of EVs
 - Brushless and no or reduced permanent magnet usage
 - Potential for unity power factor operation to reduce inverter kVA rating
- Approach
 - Die compressed windings for high slot fill
 - Capacitive power transfer using mechanically simple PCBs
- Technical Accomplishments
 - Multi-material magneto-structural topology optimization
 - WFSM with rotor die compressed winding prototyped
 - Two HESMs prototyped with one provisional patent filed
 - Multiple high performance WFSM control techniques developed
 - Mechanically simple PCB CPC and 2 MHz GaN inverter
- Future Work
 - Finish construction of final WFSM prototype with die compressed stator and field windings
 - Full power dynamometer testing with CPC and brushes and slip rings

USDRIIVE 2020/2025 WFSM/HESM Targets
Have Been Met in Simulation

Metric	2020 Target	2025 Target	Est. Final 70 mm stack WFSM
Peak Power (kW)	55	100	151
Cont. Power (kW)	30		151 (Not limited by cooling)
Specific Power Density (kW/kg)	1.6		6.28
Vol. Power Density (kW/l)	5.7	50	42.68

Technical Back-Up Slides



Technical Accomplishments – Segmented Lamination Design Tolerances

Using Laser Cut Parts

- Depending on the slot design die compressed windings may require segmented laminations
- Segmented laminations normally produced using stamping die
- Segmentation of the rotor and stator laminations has a major impact on the ease of assembly and power conversion performance
- Laser cut, stacked, and bonded laminations have a typical stack tolerance of $\pm 0.003''$ (though this will not be guaranteed typically by the manufacturer)
- Surface roughness is not guaranteed
- Series of dovetail joints of varying fits has been designed to be laser cut to determine best assembly and shrink fit tolerances

